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Surface and Subsurface Phosphorus Losses from Fertilized Pasture Systems in Ohio

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ABSTRACT

Phosphorus is an essential plant nutrient and critical to agricultural production, but it is also a problem when excessive amounts enter surface waters. Summer rotational grazing and winter feeding beef pasture systems at two fertility levels (56 and 28 kg available P ha^{-1}) were studied to evaluate the P losses from these systems via surface runoff and subsurface flow using eight small (0.3–1.1 ha), instrumented watersheds and spring developments. Runoff events from a 14-yr period (1974–1988) were evaluated to determine the relationships between event size in mm, total dissolved reactive phosphorous (TDRP) concentration, and TDRP transport. Most of the TDRP transported was via surface runoff. There were strong correlations (r^2 = 0.45–0.66) between TDRP transport and event size for all watersheds, but no significant (P = 0.05) correlations between TDRP concentration and event size. Flow-weighted average TDRP concentrations from the pasture watersheds for the 14-yr period ranged from 0.64 to 1.85 mg L^{-1} with a few individual event concentrations as high as 85.7 mg L^{-1}. The highest concentrations were in events that occurred soon after P fertilizer application. Average seasonal flow-weighted TDRP concentrations for subsurface flow were <0.05 mg L^{-1}. Applying P fertilizer to pastures in response to soil tests should keep TDRP concentrations in subsurface flow at environmentally acceptable levels. Management to reduce runoff and avoidance of P fertilizer application when runoff producing rainfall is anticipated in the next few days will help reduce the surface losses of P.

Phosphorus is one of the essential nutrients for all living things, but excessive amounts in surface waters can cause excessive growth of aquatic biota. Such accelerated eutrophication can limit water use for drinking, recreation, and industry in water bodies near the source of the excess P as well as at great distances from the P sources. Agricultural systems have been clearly linked with P movement into surface water bodies (Cassell et al., 1998; Correll, 1998; Sharpley et al., 1994). Various aspects of P movement and its impacts have been studied extensively. Considerable literature on the impacts of agricultural P on eutrophication has been reviewed (Daniel et al., 1998; Correll, 1998) including P loss in agricultural drainage (Sims et al., 1998).

Much of the research on the impacts of P management in the United States has dealt with non-forage crops. Phosphorus from pasture systems has received considerable attention outside the United States, especially in Australia, New Zealand, and the United Kingdom. New Zealand research on P in pasture runoff was reviewed by Gillingham and Thorrold (2000). There is an increasing amount of research on direct fertilizer effects on P runoff from agricultural systems that were mainly pastoral (reviews by Nash and Halliwell, 1999; Hart et al., 2004). Research on P movement in surface runoff from pasture systems at various scales was reviewed by Dougherty et al. (2004).

One of the difficulties in addressing P movement to surface water is that the critical P concentration above which eutrophication may occur is an order of magnitude smaller than the P concentrations in the soil solution critical for plant growth (Daniel et al., 1998). Additionally various water quality standards for P have been established for receiving waters. To control eutrophication total phosphorus (TP) should not exceed 0.05 mg L^{-1} in streams entering lakes and reservoirs, nor 0.025 mg L^{-1} within lakes and reservoirs (Daniel et al., 1998). For lowland streams in New Zealand, the Australian and New Zealand Environment and Conservation Council (2000) set limits of 0.01 and 0.033 mg P L^{-1} for dissolved reactive phosphorus (DRP) and TP, respectively. Primary algal production requires a P concentration of >0.02 mg L^{-1} (Hayes and Green, 1984). Dissolved reactive P may cause eutrophication in lowland rivers around 0.01 mg L^{-1} (Meybeck, 1982; Australian and New Zealand Environment and Conservation Council, 2000). In a laboratory study of 11 species of freshwater algae, Grover (1989) found that PO_4–P levels required to maintain equilibrium algal growth ranged from 0.003 to 0.8 μg L^{-1}. Research of Sawyer (1947) and Vollenweider and Kerekes (1980) suggested that critical P concentrations above which accelerated eutrophication may occur are 0.01 and 0.02 mg L^{-1} for dissolved P and TP, respectively. Correll (1998) stated that TP may be more meaningful in evaluating eutrophication enhancement. In the 1970s eutrophication and TP concentrations increased in the Chesapeake Bay while dissolved P concentrations remained relatively unchanged. Although acceptable concentrations of TP may vary with the situation, for most surface bodies of water TP concentrations of 0.1 mg L^{-1} are unacceptably high and concentrations of 0.02 mg L^{-1} are often a problem (Correll, 1998).

Using rainfall simulators on grassed plots to relate dissolved P in surface runoff to soil test P, several studies in the United States (Pote et al., 1999a, 1999b; Schroeder et al., 2004; Torbert et al., 2002) reported dissolved P concentrations ranging up to nearly 2.0 mg L^{-1}. Based on this type of information, Vadas et al. (2005) concluded that soil test P can be a good predictor for dissolved P in surface runoff from non-calcareous soils. Pierson et al. (2001) recommended caution, however, when using such relationships if poultry litter was the P source and soil test P was determined shortly after a litter application. They also reported that dissolved P concentrations in

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Abbreviations: TDRP, total dissolved reactive phosphorus; TP, total phosphorus; WS, watershed.

runoff were as high as 19 mg L^{-1} when runoff occurred immediately after a surface application of broiler litter.

Season of the year, improved drainage, and storm intensity have also been shown to affect P concentrations and transport in surface runoff. McDowell and Wilcock (2004) noted that total P concentrations in stream flow from four predominantly pastoral New Zealand catchments were highest in the summer (site averages = 0.076–0.160 mg L^{-1}) and were usually lowest in the autumn (0.044–0.057 mg L^{-1}). High levels of soil P in these catchments were a major factor contributing to TP concentrations in runoff exceeding Australian and New Zealand Environment and Conservation Council limits. In drained and undrained pastures in New Zealand, TP concentrations in surface runoff were similar, ranging up to nearly 5 mg L^{-1}, but transport was reduced because surface runoff was much less in the drained pastures (Smith and Monaghan, 2003). Using 1-ha plots in the UK, Hawkins and Scholefield (1996) measured higher molybdate-reactive phosphorus (MRP) concentrations and transport in surface runoff from undrained plots than from drained plots. They concluded that this type of grassland system has the potential to be an important source of diffuse P to surface waters. On the same plots Haygarth and Jarvis (1997) measured higher TP concentrations and transport from low frequency, high intensity runoff events than from high frequency, low intensity events. Concentrations of P leaving the grazed grassland from some high intensity storms were high enough to cause eutrophication. In the southeastern Coastal Plain of the United States, Novak et al. (2003) reported that more dissolved P was transported from a watershed with high density of animal production in baseflow than stormflow. Nevertheless, intense summer storms greatly increased the dissolved P transported out of the watershed.

In an effort to further characterize P transport in pastures, we analyzed 14 years of runoff data and 10 years of ground water data from multiple watersheds. Our objectives were to investigate the interrelationships between surface runoff, event size, event TDRP concentration, and TDRP transport from pasture management systems at two fertility levels; and to compare concentrations and transport in surface runoff with the TDRP transport in shallow ground water. A better understanding of the factors contributing to TDRP loss from grasslands should aid the development of improved management practices.

MATERIALS AND METHODS

The study was conducted at the North Appalachian Experimental Watershed (NAEW) near Coshocton, Ohio, USA (Fig. 1). Two rotationally grazed pasture management systems at high and medium fertility levels were used. A spring calving beef herd grazed four pastures during the summer in each system. Cattle (*Bos taurus*) were usually in a pasture 5 to 7 d before being moved to the next pasture.

High Fertility Pasture System

The high fertility experimental area (24.0 ha) received 224 kg N ha^{-1} per year initially. Fertilizer and lime were broadcast ap-

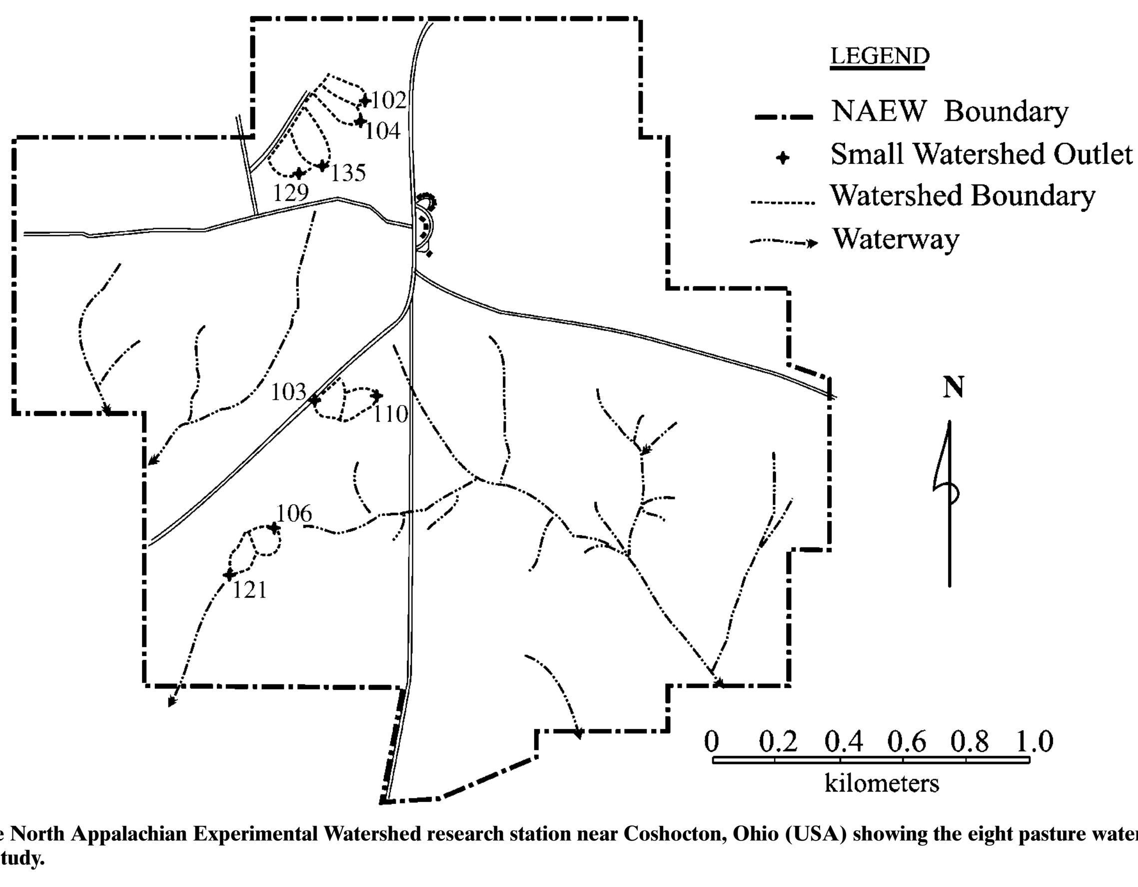

Fig. 1. The North Appalachian Experimental Watershed research station near Coshocton, Ohio (USA) showing the eight pasture watersheds used in this study.

plied according to soil tests (Fig. 2) to maintain a topsoil pH of 6.5 to 7.0 and available P and K levels of 56 and 336 kg ha^{-1}, respectively (Table 1). Phosphorus was added as superphosphate in fertilizer blends. Soil test soil samples were usually taken in the fall to a depth of 15 cm. This area was divided into eight pastures, four of which contained an instrumented water-

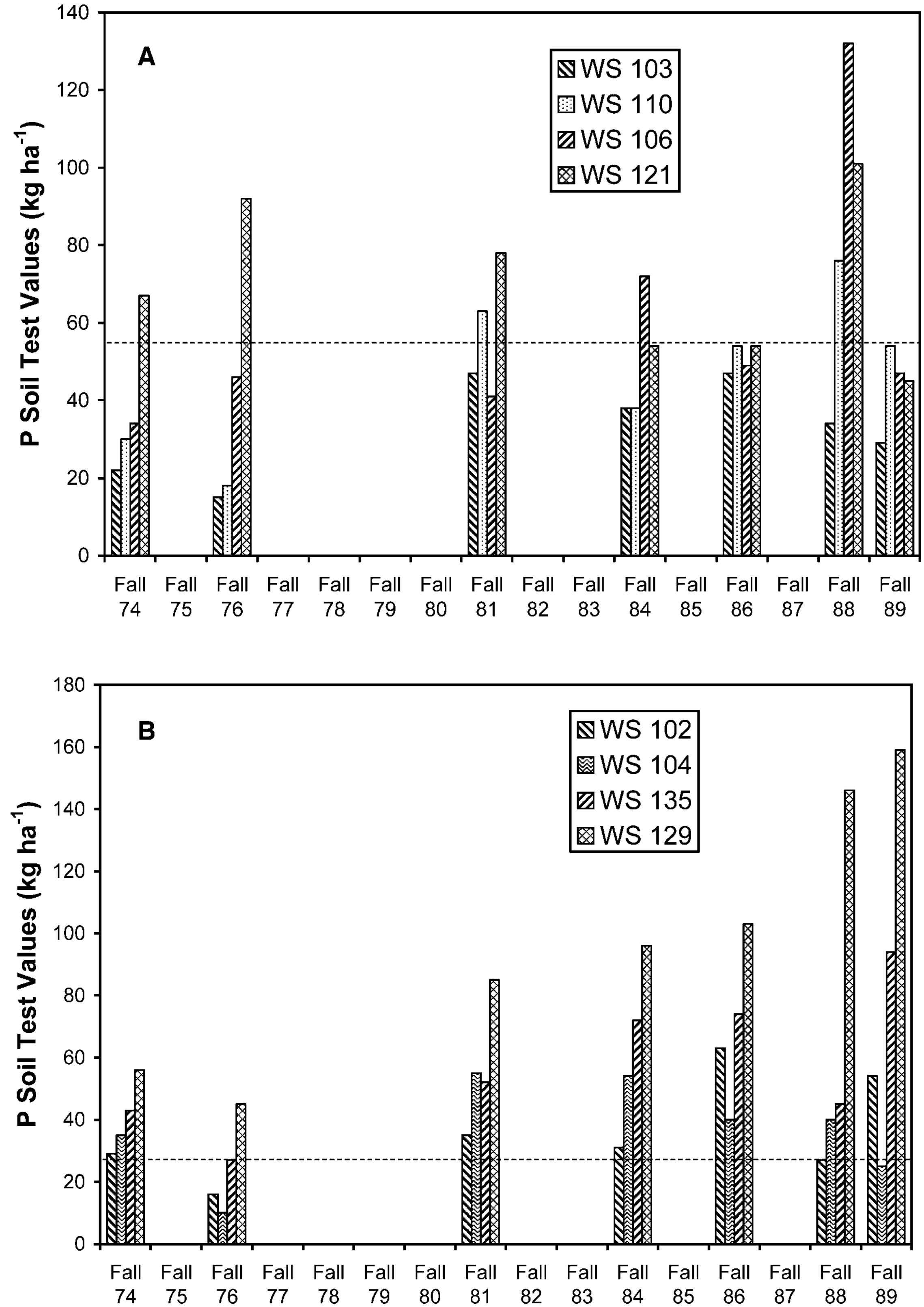

Fig. 2. Phosphorus soil test values for the high fertility pastures (A) with the horizontal dotted line being the desired P level of 56 kg ha^{-1}, and for the medium fertility pastures (B) with the horizontal dotted line being the desired P level of 28 kg ha^{-1}.

Table 1. Timing of P fertilizer applications by watershed (month of application) and amount of P applied.

Watershed (WS)	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
	Month of application, amount of P applied (month, kg ha^{-1})													
	High fertility pastures													
Summer grazing														
103	May, 83†		Mar, 67‡		Apr, 81‡		Apr, 87‡	Aug, 111§	Nov, 67¶	Oct, 65¶	Sep, 40¶		Oct, 155§	Sep, 40¶
110	May, 83†		Mar, 67‡		Apr, 81‡		Apr, 87‡	Aug, 111§	Nov, 67¶	Oct, 64¶	Sep, 40¶		Oct, 155§	Sep, 40¶
Winter feeding														
110	May, 83†		Mar, 67‡		Apr, 71‡		Apr, 87‡	Aug, 111§	Nov, 67¶	Oct, 64¶	Sep, 40¶		Oct, 155¶	Sep, 40¶
106	May, 48†		May, 56‡		Apr, 71‡		Apr, 87‡	Aug, 102§	Nov, 67¶	Dec, 54¶	Sep, 44¶		Oct, 54¶	Sep, 40¶
	Medium fertility pastures													
Summer grazing														
102									Nov, 39¶			Oct, 40¶		
104	May, 134‡								Nov, 41¶					Sep, 40§
135	May, 160§								Nov, 38¶					
Winter feeding–summer grazing														
129	May, 57§													

† 6–24–24.
‡ 0–24–24.
§ 0–46–0.
¶ 0–12–46.

shed (WS) for determining surface runoff. Four pastures with two watersheds (WS 103, 0.3 ha; WS 110, 0.6 ha) were orchardgrass (*Dactylis glomerata* L.) summer pastures. During the dormant periods (November–April), cows were moved through four tall fescue (*Festuca arundinacea* Schreb.) pastures (WS 106, 0.7 ha; WS 121, 0.6 ha) to graze fall regrowth, and to use tall fescue hay that had been grown and stored in these pastures during the summer. After 5 yr alfalfa (*Medicago sativa* L.) was interseeded into the grasses and no N fertilizer was added (Owens et al., 1994). Available P and K soil levels were maintained. Other management details were reported by Owens et al. (1998).

The slopes of the summer grazed pastures ranged from 2 to 18%, with an average of approximately 12%, and in the winter pastures slopes ranged from 6 to 25% with an average of approximately 15%. Subsurface flow was sampled at springs on the outcrop of the Lower Kittanning clay, a nearly impermeable layer that maintains a perched aquifer at an elevation a few meters lower than the watershed outlets. The Middle Kittanning clay outcrops midway down the slope within WS 103 and WS 110. The soils in the watersheds (Rayne, Keene, and Coshocton series) are residuum derived silt loams that are well-drained (Typic Hapludults) above the Middle Kittanning clay outcrop and moderately well-drained (Aquic Hapludalfs) below the outcrop. Subsurface flow from WS 106 and WS 121 was sampled at springs on the outcrop of the Middle Kittanning clay. Soils in this area (Rayne, Berks, and Dekalb series) are also well-drained residual silt loams (Typic Dystrochrepts and Hapludults).

Medium Fertility Pasture System

The medium fertility pasture area (17.2 ha) received 56 kg N ha^{-1} per year initially. Fertilizer and lime were broadcast applied according to soil tests (Fig. 2) to maintain a topsoil pH of 6.0 and available P and K levels of 28 and 168 kg ha^{-1}, respectively (Table 1). This area was divided into four pastures, each with an instrumented watershed for determining surface runoff (WS 102, 0.5 ha; WS 104, 0.5; WS 129, 1.1 ha; WS 135, 1.1 ha). The predominant vegetation was orchardgrass and Kentucky bluegrass (*Poa pratensis* L.). Cattle grazed all four pastures during the summer but were moved to one pasture (WS 129) during the dormant period where they were fed hay, grown elsewhere on the station. After 5 yr the annual N fertilizer rate was increased to 168 kg ha^{-1} (Owens et al., 1992) except in WS 129 where the annual N contribution from hay was nearly 300 kg ha^{-1} (Owens et al., 1982). Available P and K soil levels were maintained. Soil, climate, geology, and geomorphology of both areas and all eight watersheds were described in greater detail by Kelley et al. (1975).

Watershed slopes range from 12 to 25%, with an average of approximately 20%. Subsurface flow was sampled at springs on the outcrop of the Middle Kittaning clay. Soils (Rayne, Berks, and Dekalb) are well-drained residual silt loams. Kelley et al. (1975) described further details for soils, climate, geology, and geomorphology.

Hydrologic Measurements

Surface runoff from the watersheds was quantified using precalibrated H-flumes housed within heated enclosures that permitted year-round measurements. Surface runoff water samples were collected during each event using Coshocton wheels (Brakensiek et al., 1979) modified to continuously deliver a flow-proportional sample of runoff water. Subsurface flow was grab sampled weekly from HS or V-notch flumes at each site.

Precipitation was measured using standard recording rain gauges in each study area. Soil moisture was measured twice monthly in the watersheds to a depth of 130 cm (near or below the rooting depth), using gravimetric samples of the 20-cm topsoil layer, and neutron probe readings in the remaining profile. Daily values of lysimeter evapotranspiration (ET) were used to interpolate soil moisture between reading dates, and the quantity of subsurface flow was calculated using a lysimeter water budget. With precipitation, soil moisture, and runoff data for the watersheds, the assumption was made that the ratio of lysimeter percolation (subsurface outflow) to ET would be the same on these adjacent lysimeters as on the watersheds (Van Keuren et al., 1979). Runoff, spring, and precipitation samples were vacuum filtered through 1.6-μm fiberglass filters and stored at 4°C until analysis.

Water and Soil Analyses

The TDRP in water samples was measured colorimetrically in acid-treated samples using a modified phosphomolybdate

Table 2. Number of runoff events categorized by the total volume of each individual runoff event from May 1974 through April 1988.

Watershed (WS)	Runoff events: Volume of runoff (mm) <0.10	0.100–0.500	0.500–1.000	1.000–5.000	5.000–10.000	10.000–25.000	>25.000	Total, average annual
High fertility pastures								
Summer grazing								
103	113	83	48	125	51	41	16	477, 34
110	124	91	23	80	21	12	3	354, 25
Winter feeding								
106	261	116	49	101	23	23	3	577, 41
121	281	90	43	97	32	26	3	572, 41
Medium fertility pastures								
Summer grazing								
102	94	42	9	36	9	3	1	194, 14
104	144	53	15	34	6	4	0	256, 18
135	67	34	21	28	9	3	1	163, 12
Winter feeding–summer grazing								
129	188	117	39	131	51	39	5	570, 41

procedure (USEPA, 1979). Soil P was determined a modified Bray and Kurtz P-1 method as described by Olsen and Dean (1965).

RESULTS AND DISCUSSION

Surface Runoff

During the 14-yr period of record (May 1974–April 1988), the average number of runoff events per watershed ranged from 12 to 41 per year (Table 2). More runoff events occurred in the watersheds used for winter feeding than in those used for summer grazing. Overall, more than 60% of the runoff events were less than 1 mm in size (40% were less than 0.1 mm). The two watersheds with the greatest percentage of events > 1 mm (WS 103 and 129) also had the greatest amounts of total runoff (Table 3). Watershed 103 is impacted by the Middle Kittanning clay outcropping in the middle of the watershed. This returned some of the shallow ground water to the surface, which probably increased the amount of runoff occurring at the watershed outlet. Watershed 129 was the only watershed with continuous cattle occupancy during the winter. This could increase runoff by reducing surface cover and increasing soil compaction. Not only did this increase the number of events ≥ 1 mm, but the number of large events (10–25 mm; >25 mm) also increased (Table 2).

Although <35% of the runoff events were ≥1 mm in six of the watersheds (WS 103 and 129 excluded), these events produced 87.0 to 94.4% of the runoff and 84.7 to 95.7% of the TDRP transport (Table 3). Except for the medium fertility winter feeding–summer grazing watershed (WS 129), the top 10 runoff events from each watershed ranked by TDRP transport quantities (Table 4) transported 38.5 to 58.0% of the total quantities of TDRP moved during the 14-yr period. In the high fertility pastures, the TDRP transport from the largest single event was always greater than the 14-yr average annual transport. This emphasized the major impacts of large events on surface TDRP loss. Having a small percentage of events responsible for a large percentage of the TDRP loss is similar to the observation at the North Appalachian

Table 3. Number of events, amount of runoff, and total dissolved reactive phosphorous (TDRP) transport for all of the surface events and only the events ≥ 1 mm for the period of May 1974 through April 1988.

Watershed (WS)	Events: Total	Events: ≥1 mm	Events: ≥1 mm	Runoff: Total	Runoff: ≥1 mm	Runoff: ≥1 mm	TDRP transport: Total	TDRP transport: ≥1 mm	TDRP transport: ≥1 mm
			%	mm	mm	%	kg ha^{-1}	kg ha^{-1}	%
High-fertility pastures									
Summer grazing									
103	477	233	48.8	1924	1864	96.7	21.8	21.0	96.6
110	354	116	32.8	665	622	93.6	5.2	5.0	94.8
Winter feeding									
106	576	150	26.0	896	827	92.3	12.0	11.3	93.5
121	572	158	27.6	1043	984	94.4	19.3	18.4	95.7
Medium fertility pastures									
Summer grazing									
102	194	49	25.2	245	225	92.0	1.6	1.4	87.5
104	256	44	17.2	232	201	87.0	2.1	1.7	84.7
135	163	41	25.2	233	208	89.6	1.8	1.6	87.0
Winter feeding–summer grazing									
129	570	226	39.6	1481	1415	95.5	19.2	18.1	94.6

Table 4. Range of total dissolved reactive phosphorous (TDRP) transport in the top 10 runoff events for each watershed ranked by transport quantities and the average annual transport for all events during the 14-yr study period.

Watershed (WS)	TDRP transport: Range of top 10	Top 10 as % of total	Average annual
	kg ha^{-1}	%	kg ha^{-1}
	High fertility pastures		
Summer grazing			
103	0.052–1.630	38.5	1.556
110	0.015–0.511	44.9	0.375
Winter feeding			
106	0.048–2.885	49.1	0.859
121	0.082–3.627	49.9	1.376
	Medium fertility pastures		
Summer grazing			
102	0.017–0.106	48.3	0.111
104	0.022–0.077	51.1	0.147
135	0.026–0.324	58.0	0.131
Winter feeding–summer grazing			
129	0.070–0.630	20.5	1.370

Experimental Watershed that a few large events carried most of the sediment from cropped watersheds (Edwards and Owens, 1991). The sediment loss was even more disproportionate than the P transport; the five largest erosion-producing events on each of nine rotationally cropped watersheds produced 66% of the total erosion over 28 yr (Edwards and Owens, 1991).

Events ≥ 1 mm transported a lower percentage of the TDRP moved (84.7–87.5%) in the medium fertility watersheds than in the high fertility watersheds (93.5–96.6%) (Table 3). The winter feeding area in the medium fertility pasture system (WS 129) had a higher percentage of TDRP transport (94.6%) in events this size than did the medium fertility summer grazing watersheds. But it also had greater additions of P because it annually received more than 50 kg ha^{-1} of P in hay and winter feed (Owens et al., 2003).

In the high fertility pastures, there were 10 events with TDRP concentrations greater than 10 mg L^{-1}; two events were more than 60 d after a P fertilizer application; and three events were <1 mm. The highest concentrations occurred soon after fertilizer application (Fig. 3). Of the events with >10 mg L^{-1} TDRP concentrations, the lowest three concentrations were the <1-mm events. The highest TDRP concentration observed (85.67 mg L^{-1}) was the result of a runoff event which occurred on the day of fertilizer application (1 Oct. 1986) to the high fertility WS 103. In the medium fertility watersheds, there were no runoff events with TDRP concentrations greater than 7.5 mg L^{-1}.

The concentration ranges for the top 10 events ranked by TDRP concentration are considerably higher in the high fertility watersheds than the medium fertility watersheds (Table 5). The winter feeding–summer grazing watershed in the medium fertility system, which had average annual P additions of 56.2 kg ha^{-1} from hay (Owens et al., 2003), has an overall weighted TDRP concentration similar to those in the high fertility pastures. Consistent with the range of top 10 concentrations in each watershed being higher than the overall weighted average for the respective watershed, a few large concentration events impact the weighted average concentrations of all events. This is shown by the differences in averages with the top 10 events being included and excluded. Nevertheless, a high concentration event probably has a greater impact by contributing a greater P "dosage" to a surface water body than by raising the average weighted concentration for all events.

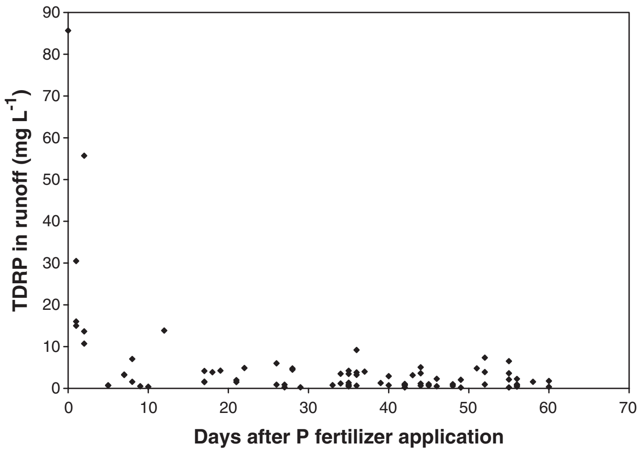

Fig. 3. Total dissolved reactive phosphorous (TDRP) concentration in surface runoff plotted against the number of days that the runoff event occurred following P fertilizer application. Only events occurring within 60 d following P fertilizer application are shown.

Regression analyses of surface runoff events indicated a stronger relationship for TDRP transport vs. size of runoff event (Fig. 4) than for TDRP transport vs. TDRP concentration (Fig. 5). Even with the stronger relationship of TDRP vs. size of runoff event, there was still some scatter of plotted data and explanation was difficult. In Fig. 2, the top five TDRP transport events (>0.5 kg ha^{-1}) showed greater transport for the event size than would be predicted by the regression equation.

Table 5. Range of total dissolved reactive phosphorous (TDRP) concentrations in the top 10 runoff events for each watershed ranked by concentration and the weighted concentrations for all events during the 14-yr study period.

Watershed (WS)	TDRP concentration: Range of top 10	Weighted average	Weighted average without top 10
	mg L^{-1}		
	High fertility pastures		
Summer grazing			
103	3.32–85.67	1.13	0.92
110	1.19–15.00	0.79	0.59
Winter feeding			
106	2.65–30.50	1.34	0.88
121	5.07–55.70	1.85	1.31
	Medium fertility pastures		
Summer grazing			
102	1.07–2.54	0.64	0.53
104	1.24–2.44	0.89	0.81
135	1.12–3.08	0.79	0.58
Winter feeding–summer grazing			
129	3.12–7.50	1.30	1.21

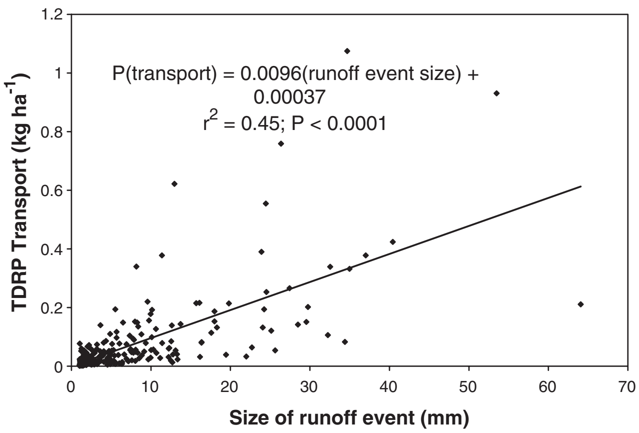

Fig. 4. Plot of total dissolved reactive phosphorous (TDRP) transport vs. size of runoff event for Watershed 103.

All of these events occurred more than 60 d after application of P fertilizer. Three events were during the winter, non-grazing period. The 0.76 kg ha^{-1} event was in June while the cattle grazed the watersheds; the 0.93 kg ha^{-1} event was in October and occurred 3 d after the cattle were rotated out of the watersheds. There was no significant relationship (P = 0.05) between TP concentration and size of runoff event (Fig. 6). This lack of correlation would indicate that there was sufficient P available to go into solution, especially for low concentrations, across a wide range of event sizes. These figures show data for WS 103, but the data from the other watersheds had similar relationships (Table 6). These results indicate that surface transport of TDRP was more dependent on the amount of runoff than concentration of TDRP, and that TDRP concentration was not dependent on the amount of runoff. Thus, to reduce surface transport of TDRP, practices that reduce surface runoff may be more important than practices that reduce TDRP concentration in runoff. Certainly reducing both runoff and concentration would have the greatest impact.

Subsurface Flow

Subsurface concentrations and transport of TDRP were considerably lower than the levels in surface runoff

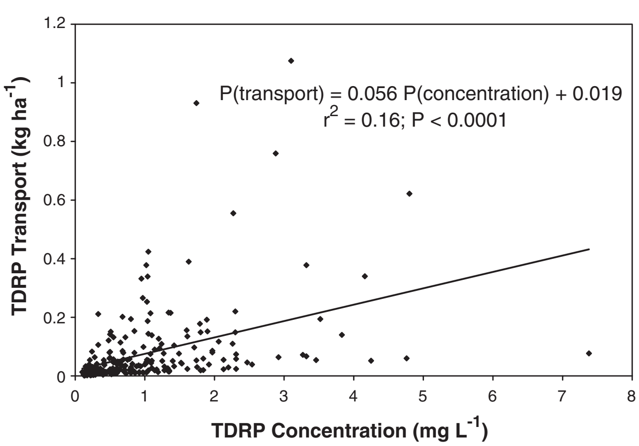

Fig. 5. Plot of total dissolved reactive phosphorous (TDRP) transport vs. TDRP concentration for Watershed 103.

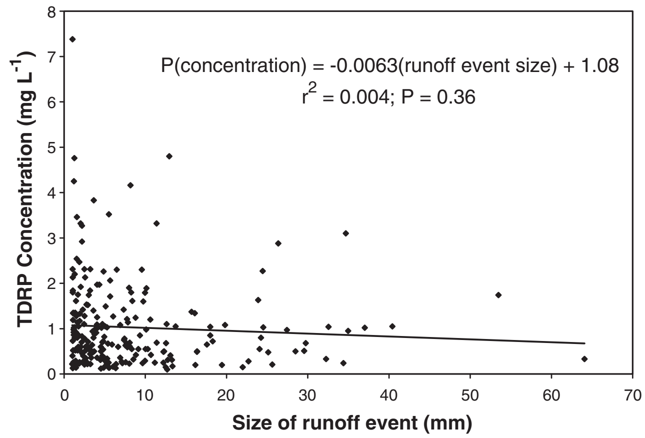

Fig. 6. Plot of total dissolved reactive phosphorous (TDRP) concentration vs. size of runoff event for Watershed 103.

(Table 7) for the 10-yr period May 1978 through April 1988. The subsurface flow during the 6-mo dormant season (November through April) was more than twice the flow during the growing season (May through October) for all watersheds. Because of this greater dormant season flow, TDRP transport was also greater during the dormant season, even though the concentrations were sometimes greater during the growing season.

Average seasonal TDRP transport and concentrations were more affected by seasonal subsurface flow than pasture fertility levels (Table 7). During the dormant season, plant water needs are much lower, and subsurface flow increases by more than twofold. The average of the growing season TDRP transport from all high fertility watersheds (0.035 ± 0.011 kg ha^{-1}) was more than a standard deviation below the average for dormant season (0.056 ± 0.013 kg ha^{-1}) TDRP transport. This was true for the TDRP transport from the medium fertility watersheds also (growing season 0.036 ± 0.010 kg ha^{-1}; dormant season 0.056 ± 0.017 kg ha^{-1}). The average TDRP transport for each season from the high fertility pastures, how-

Table 6. Pasture watershed R^2 values for total dissolved reactive phosphorous (TDRP) transport vs. size of runoff event, TDRP transport vs. TDRP concentration, and TDRP concentration vs. size of runoff event.

Watershed (WS)	TDRP transport vs. size of runoff event	TDRP transport vs. TDRP concentration	TDRP concentration vs. size of runoff event
	High fertility pastures		
Summer grazing			
103	0.45***	0.16***	0.004
110	0.68***	0.21***	0.008
Winter feeding			
106	0.51***	0.28***	0.000
121	0.38***	0.25***	0.000
	Medium fertility pastures		
Summer grazing			
102, 104, 135	0.66***	0.08***	0.012
Winter feeding–summer grazing			
129	0.60***	0.11***	0.006

*** Significant at the 0.001 probability level.

Table 7. Average seasonal transport and concentration (flow-weighted) of total dissolved reactive phosphorous (TDRP) from May 1978 through April 1988.

Watershed (WS)	Season	Surface runoff Flow	Surface runoff Transport	Surface runoff Concentration	Subsurface flow Flow	Subsurface flow Transport	Subsurface flow Concentration
		mm	kg ha^{-1}	mg L^{-1}	mm	kg ha^{-1}	mg L^{-1}
High fertility pastures							
Summer grazing							
103	growing	59	0.79	1.33	98	0.028	0.03
	dormant	99	1.23	1.25	212	0.065	0.03
110	growing	23	0.17	0.75	113	0.025	0.02
	dormant	30	0.31	1.03	250	0.038	0.02
Winter feeding							
106	growing	19	0.14	0.76	116	0.034	0.03
	dormant	54	1.02	1.89	220	0.051	0.02
121	growing	20	0.15	0.73	111	0.054	0.05
	dormant	51	1.28	2.51	226	0.071	0.03
Medium fertility pastures							
Summer grazing							
102	growing	12	0.08	0.64	100	0.024	0.02
	dormant	8	0.03	0.45	251	0.037	0.02
104	growing	14	0.13	0.93	101	0.031	0.03
	dormant	3	0.04	1.11	261	0.046	0.02
135	growing	13	0.13	0.98	105	0.037	0.04
	dormant	6	0.03	0.52	246	0.058	0.02
Winter feeding–summer grazing							
129	growing	58	0.63	1.09	131	0.052	0.04
	dormant	42	0.65	1.54	264	0.082	0.03

ever, was within a standard deviation of the corresponding seasonal average from the medium fertility pastures. Flow-weighted seasonal TDRP concentrations had similar relationships, differing more between seasons than between pasture fertility levels.

Annual losses of TDRP were small from both pasture systems, ≤2.0 and <0.15 kg ha^{-1} in surface runoff and subsurface flow, respectively, and these losses probably are of no economic concern. Seasonal TDRP concentrations for the subsurface flow range from 0.015 to 0.049 mg L^{-1} and may not pose an environmental problem. Daniel et al. (1998) suggested that to control eutrophication in lakes and reservoirs, TP should not exceed 0.05 mg L^{-1} in the contributing streams. Thus, our results suggest that if P is in balance for plant needs (i.e., soil is not overloaded with P as indicated by soil tests), P concentrations in shallow ground water under pasture systems should not be an environmental problem.

Seasonal TDRP concentrations in surface runoff ranged from 0.45 to 2.51 mg L^{-1} (Table 7), and individual runoff events had much higher concentrations (Table 5). These concentrations far exceeded the published values for total P concentrations that may cause eutrophication in surface water bodies. To reduce such impacts, this runoff would need to be diluted with runoff from other sources with much lower TDRP concentrations, and/or used with a conservation practice to reduce P concentration before entering surface water bodies. Alternatively, in-field practices that reduce the amount of runoff by increasing infiltration, such as reducing compaction and increasing density of grass stand, could reduce TDRP transport. Avoiding application of P containing fertilizer if runoff producing rain is anticipated within the next few days could reduce P concentrations in the runoff.

CONCLUSIONS

Phosphorus in surface waters, even at low concentrations, may promote eutrophication and subsequent detrimental environmental impacts. Agriculture is among the contributors of P to surface waters, and the magnitude of P "contributed" varies with management practice. Phosphorus is lost from the agricultural systems by surface runoff and subsurface flow. In the pasture systems investigated with nutrients balanced based on soil tests, P loss in subsurface flow was small, and the TDRP concentrations were lower than the levels usually considered to cause eutrophication. Surface runoff varied in the amount of runoff and the amount of P transported from the system. Several runoff events had TDRP concentrations well above levels that pose an environmental problem, with the highest levels occurring when runoff occurred soon after fertilizer application. There was a much stronger correlation between the amount of TDRP transported and the size of the runoff event than between the amount of TDRP transported and the TDRP concentration. The top 10 runoff events transported 39 to 58% of the total P during the 14-yr period indicating that infrequent, large storms that produced a large amount of runoff dominate P transport in these pastured watersheds. This indicates that management to reduce runoff would be more effective in reducing P loss than management practices that reduce P concentrations, although management practices that reduce both would have the greatest effect.

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